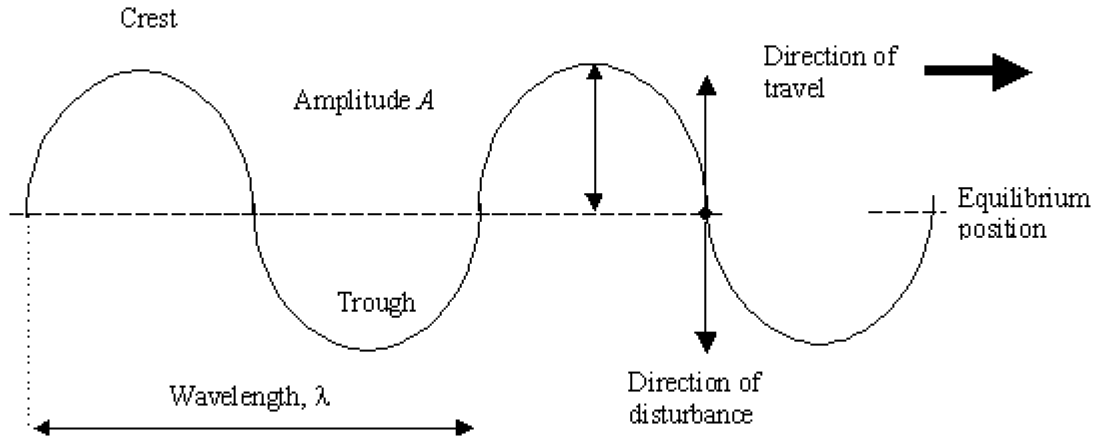
N4 N5

Physics Department

Unit 3 - Waves and Radiation

Summary Notes



3.1 Wave Characteristics

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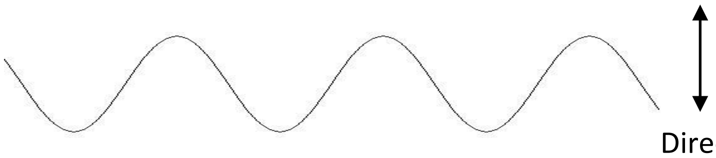
A wave transfers energy from one place to another. Waves are made from particles vibrating. In this unit we will consider two types of waves, transverse waves and longitudinal waves.
A transverse wave is one in which the vibrations making up the waves are at right angles to the direction of the wave.



Direction of vibration of particles.

Direction of wave

Waves on a rope, water waves, light waves and all members of the electromagnetic spectrum are transverse waves.

A longitudinal wave is one in which the vibrations are in the same direction as the wave travels.

Direction of vibration of particles

Direction of wave

Sound is a longitudinal wave.

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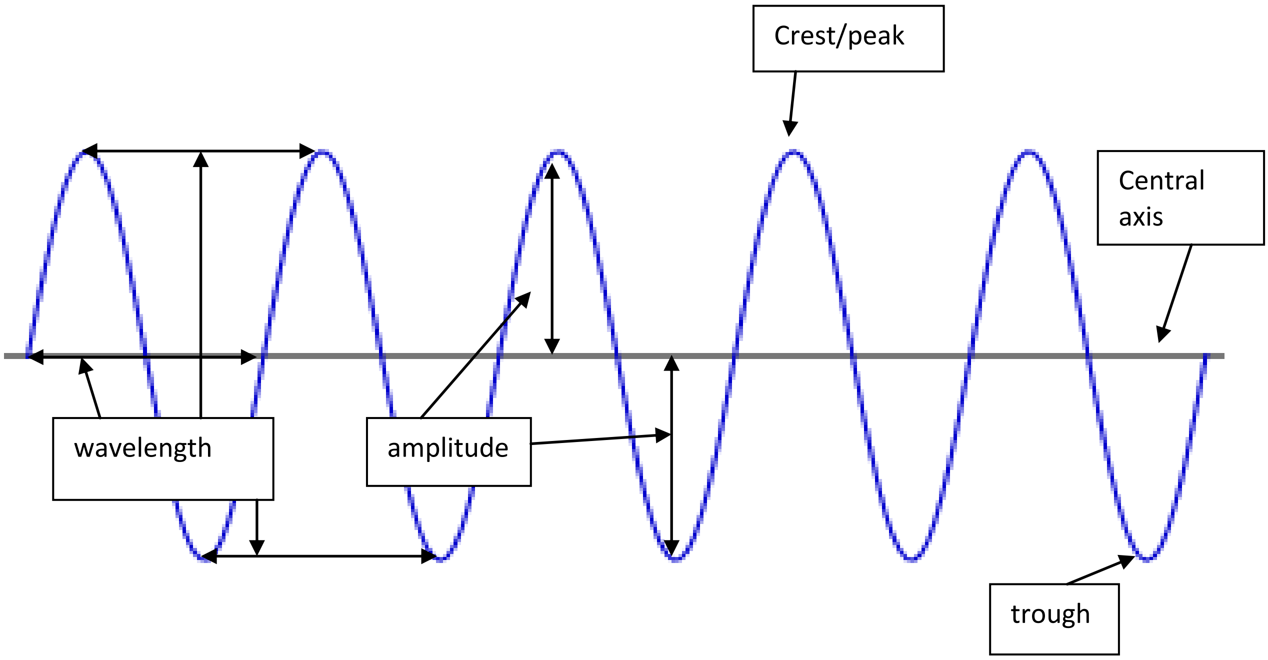
Wave Properties



Frequency, f – the number of waves produced (passing a point) each second, unit: Hertz (Hz)

$$f = N/t$$

Wavespeed, v – distance travelled by a wave in one second, unit: metres per second (m/s)

$$v = d/t$$

amplitude – size of the maximum disturbance from the central axis (distance from central axis to crest/trough), unit: metres (m)

Wavelength, λ – distance from one point on a wave to the same point on the next wave, unit: metres (m)

Period , T – time taken to produce a wave, unit: seconds (s)

$T = 1/f$ OR $T = t/N$ where N is the number of waves and t is the time.

Loud notes have more energy than quiet notes and therefore have a larger amplitude. High pitch notes produce more waves per second and therefore have a higher frequency.

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Wave Relationships

Speed, distance and time:

Relationship:	distance	=	speed	x	time
Symbol:	d		v		t
Unit:	metres		meters per second		
Abbreviation:	m		m/s		s

The Wave Equation:

Relationship:	speed	=	frequency	x	wavelength
Symbol:	v		f		λ
Unit:	Metres per second		hertz		metres
Abbreviation:	m/s		Hz		m

Examples: A wave travels 90 metres in 30 seconds. Calculate the speed of the wave.

$d = vt$
$90 = v \times 30$
$v = 90 / 30$
$v = 3$ meters per second

A wave has a wavelength of 0.5 metres and a frequency of 4 hertz. What is its speed?

$v = f\lambda$
$= 4 \times 0.5$
$= 2$ meters per second

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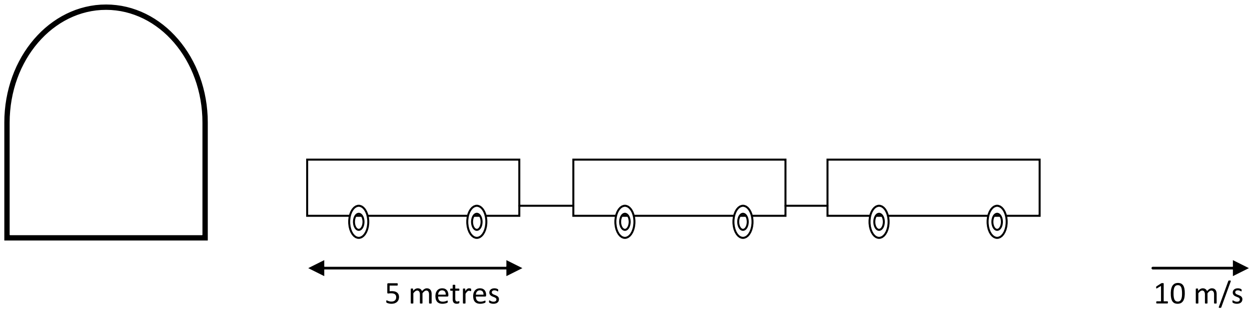
A wave analogy

Suppose a goods train is coming out of a tunnel at a speed of 10 metres per second and the trucks are 5 metres long.



Every second, **10 metres** of train exits the tunnel.
Every second **2**carriages exit the tunnel.
The frequency of the carriages is **2** per second.
Each "carriage length" is **5** metres.
The speed of the train is **10** metres per second.
The link between speed, frequency of the carriages and carriage length is:
Speed = frequency x carriage length
If the carriage length were replaced with wavelengths the equation becomes:
Speed = frequency x wavelength
v = f x λ

A mathematical derivation

If you are watching waves in a pond, you can time how long it takes a whole wavelength to pass a point by timing from one crest to the next. You can also measure the distance from one crest to the next to find the wavelength.

Using these measurements the speed of the wave can be calculated from:

$$v = \frac{d}{t}$$

Since you measured one wave, d = λ (the wavelength) and t = T (the period).
Therefore,

$$v = \frac{\lambda}{T}$$

But we know that $T = \frac{1}{f}$

Therefore, $$v = \frac{\lambda}{\frac{1}{f}}$$

So $$v = f\lambda$$

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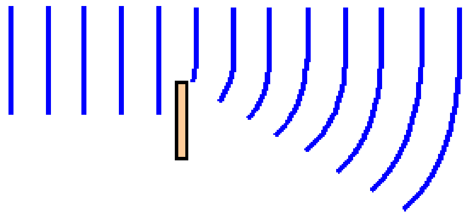
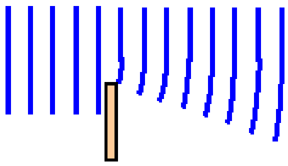
Diffraction

Waves are able to bend around obstacles. This bending of waves around corners is called **diffraction**. Long wavelength waves diffract more than short wavelength waves.



Long wavelength



Short wavelength

As longer wavelengths diffract more than short wavelengths, radio transmissions from ground stations are more likely to be received than shorter wavelength TV waves.

3.2 Sound

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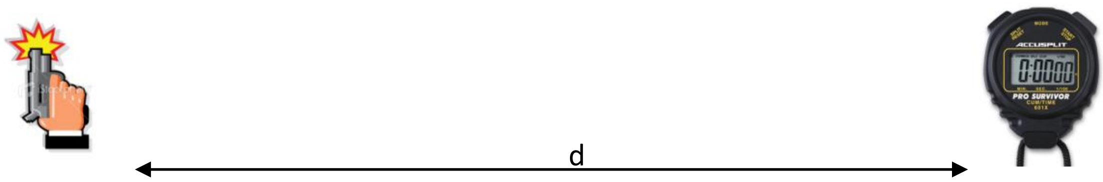
Sound waves can only be transmitted through solids, liquids and gases. Sound cannot travel through a vacuum as a vacuum does not contain particles. The speed of sound in air varies but is approximately 340 metres per second which is much slower than the speed of light in air at 300 000 000 metres per second..

Speed of sound in air

We will consider two methods to measure the speed of sound in air.

Method 1

An observer with a stopwatch stands a long distance away from a starter at an athletics meeting. When the starter fires their starting pistol, the observer sees the flash from the gun instantly and hears the sound after a short delay. The observer starts their stopwatch as soon as they see the flash and stop it when they hear the sound. Using the distance, d, travelled by the sound (which must be measured) and the time, t, for the sound to travel to them (from the stopwatch) the speed of sound can be calculated from: $d = vt$.



This is not a particularly accurate method as it relies on human reaction time.

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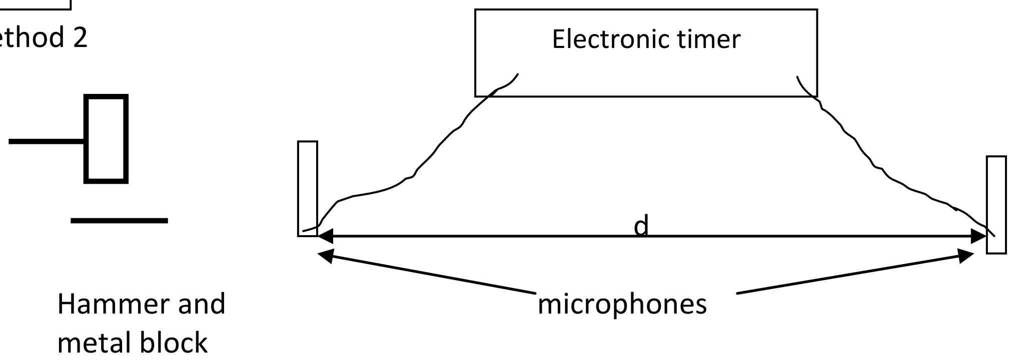
Speed of sound in air

Method 2



The distance, d, is measured with a metre stick. The hammer is struck against the block. As the sound reaches the first microphone the timer is started, when it reaches the second microphone the timer is stopped. The equation $d = vt$ is used to calculate the speed again. This is a much more accurate method.
The exact value for the speed of sound in air can vary, however it is around **340 m/s**.

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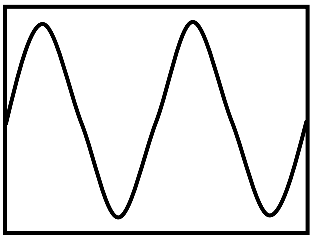
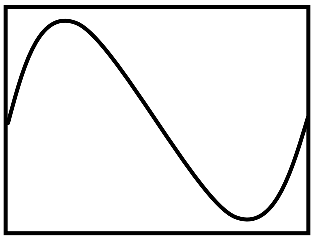
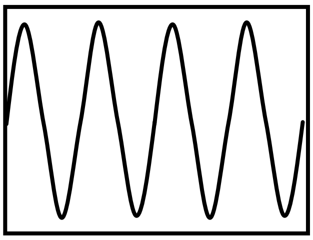
Amplitude and frequency

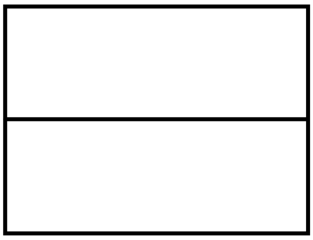
An oscilloscope can be used to analyse wave patterns and what effect changing certain properties has on the shape of a wave.

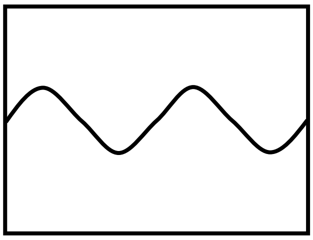

original sound

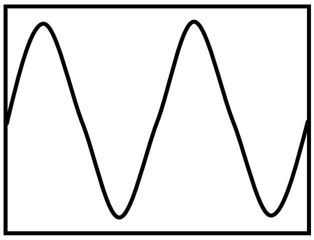

frequency lower


frequency higher

Waves with a low frequency would be low pitched and waves with a high frequency would be high pitched.


no sound


quiet sound


LOUD SOUND

Waves with a small amplitude would be quiet and those with a large amplitude would be loud.

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Decibel scale and noise pollution

Noise pollution is any unwanted sound. Noise levels are measured in **decibels** (dB). These can be measured using a sound level meter. Regular exposure to sounds above 85-90dB can cause damage to hearing. Some typical noise levels are given below

Situation	Decibels
Threshold of human hearing	0
Leaves rustling in the wind	20
Whisper, rustling paper	30
Quiet residential area at night	40
Inside average home	50
Normal conversation at 1m distance	60
Phone ringing, busy street	70
Alarm clock at 0.5 m distance	80
Threshold of hearing damage	85
Truck heard from pavement, busy factory	90
Hair dryer	100
Lawn mower at a distance of 1m	110
Rock concert 1m from loudspeaker, vuvuzela horn at a distance of 1m	120
Jet engine at a distance of 50m	130
Threshold of pain	120 - 140
Stun grenade	180

We can protect against damage to hearing by loud noises by wearing ear plugs or ear protectors. Ear protectors, sometimes called ear defenders, work by absorbing sound energy. This reduces the amplitude of the sound wave.

Short term exposure to sound levels over 140 dB may give rise to pain and cause temporary and sometimes permanent damage to hearing. Excessively loud noises can cause damage to the hair cells in the inner ear. A “ringing” sound heard after exposure to loud noise is a warning that damage may have been caused.

High frequency deafness is a condition where a human has difficulty in hearing frequencies in the upper limits of the range of human hearing. The normal range of human hearing is between 20 hertz and 20 000 hertz, although there is considerable variation between individuals, especially at the high frequency end, where a gradual decline with age is considered normal.

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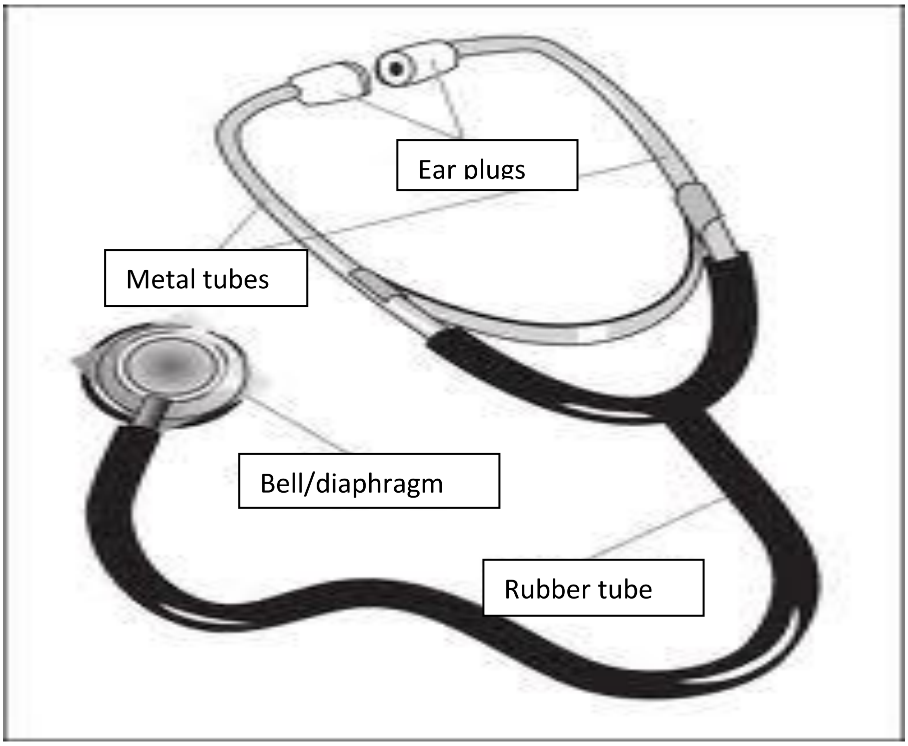
Sound in medicine

A stethoscope is a device which allows a doctor to listen to sounds from inside the body like heart and lung sounds.



The end placed next to the patient has two bells. One is open and the other is closed by a thin semi-rigid disc called the diaphragm.

- The open bell is used to listen to heart sounds.
- The closed bell is used to listen to higher frequency lung sounds.

The sound is picked up by the bell and passed through the air inside the tubes to the earpieces. The earpieces have to be a good fit with the doctor's ears to stop sound loses and to prevent background sounds from mixing with the sounds from the heart and lungs.

Sonar and ultrasound

Humans can hear sounds with frequencies between 20Hz and 20000Hz. Sounds with a frequency above 20000Hz are called **ultrasound**.

Ultrasound can be used to examine a foetus in the womb. A picture is built up by timing how long it takes to receive an echo from an ultrasound pulse. Ultrasound can also be used to break up kidney stones without the need for invasive surgery. Ultrasound can also be used by physiotherapists in the treatment of sports injuries.

Boats and submarines use **sonar** to detect shoals of fish, the sea bed or other submarines. Pulses of sound are sent out and then the echo is detected. This is similar to how bats and dolphins use echolocation.

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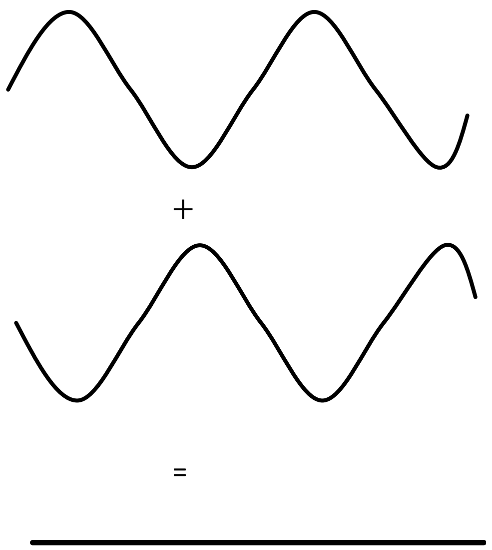
Sound reproduction and noise cancellation

Sound is an **analogue** signal. This means that it varies continuously over a range of values. Most recording technology nowadays uses **digital** technology. Digital signals can be one of two values with nothing in between. Analogue to digital converters are used to process the sound signal so that it can be transmitted easier, then a digital to analogue device allows the sound to be reproduced faithfully at the other end.

If two waves travelling in opposite directions were to meet, the result would be that they cancel each other out. The same would happen any time a crest of one wave meets a trough of another.



This effect is called interference of waves. We can make use of this effect in noise cancelling technology.

Noise cancelling headphones use a technique called "active noise control", to block out background sound to allow you to hear the sound fed through the headphones more clearly. For example:

- blocking out aircraft engines when you are trying to listen to music on your MP3 player.
- Blocking out rotor noise on a helicopter to allow you to speak to someone else inside the helicopter.

This cancellation is done in an electronic circuit. The active noise cancellation works in the circuit by detecting the unwanted outside noise signal and generating the exact same noise signal but the inverse of it. Since the two signals are equal but opposite they cancel each other out. Since the circuit requires energy to work, the noise cancelling headsets must have their own power source such as a battery to work.

Do some research of your own to find out about noise cancellation in Humvees.

3.3 Electromagnetic spectrum

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Electromagnetic spectrum

There are a number of waves which travel at the speed of light. They are all part of the **electromagnetic spectrum**. These waves are all transverse waves and travel at 300 000 000 m/s (3 x 10^8m/s) in a vacuum.

The different parts of the electromagnetic spectrum differ in wavelength and frequency

Increasing wavelength ↓		increasing frequency ↑
	Gamma rays	
	X-rays	
	Ultraviolet	
	Visible light	
	Infrared	
	Microwaves	
	TV and Radio	

The different parts of the electromagnetic spectrum can also be distinguished by their energy. Higher frequency electromagnetic radiation has a greater amount of energy than lower frequency electromagnetic radiation.

Some information on each part of the spectrum is given below

Type of e-m radiation	Typical source	Application	Detector	Possible hazard
Radio & TV	Electrical antennae	Telecommunications	Aerial	Potential increased cancer risk
Microwaves	Cosmic sources, magnetron	Cooking, Telecommunications	Diode probe	Heating of body tissues
Infra-red	Heat-emitting objects	Thermograms	Phototransistor, blackened thermometer	Over heating of body tissues causing dehydration
Visible light	Stars	Vision	Eye, photographic film	Intense light can damage the retina
Ultraviolet	Sunlight	Treating skin conditions	Fluorescent paint	Skin cancer
X-rays	X-ray tube, cosmic sources	Medical imaging	Photographic plates	Destroys cells which can lead to cancer
Gamma rays	Nuclear decay	Treating tumours	Geiger–Müller tube and counter	Destroys cells which can lead to cancer

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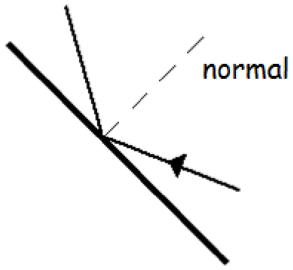
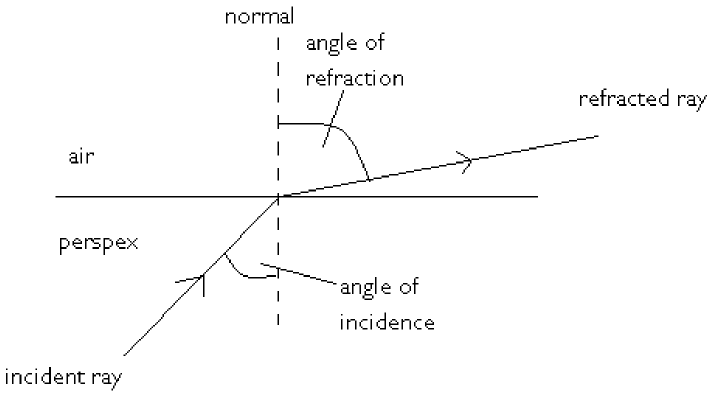
Light

Reflection
The law of reflection states that the angle of incidence is equal to the angle of reflection. Remember that all angles in a ray diagram are measured from the normal.

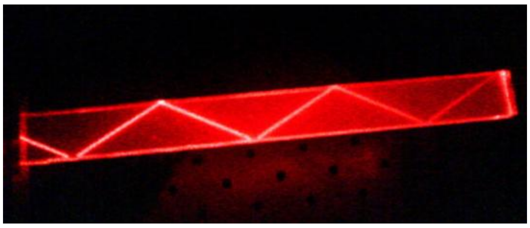


Refraction
At the boundary between different types of materials, the speed of the light wave changes. This results in a change in wavelength, and can often cause the direction of a wave to change.

The change in light speed when going from one medium into another is known as **refraction**. This effect is used in lenses.



Above a certain angle of incidence, refraction no longer occurs, and instead the light wave is reflected back into the medium where it came from. This is known as **total internal reflection.** The minimium angle of incidence that causes the wave to undergo total internal reflection is called the **critical angle.**



Total internal reflection is used in optical fibres. Optical fibres can be used for communication or in medical applications to allow doctors to see into the body. One bundle of fibres carries light into the body whilst another carries the light back out of the body. This instrument is known as an **endoscope**.

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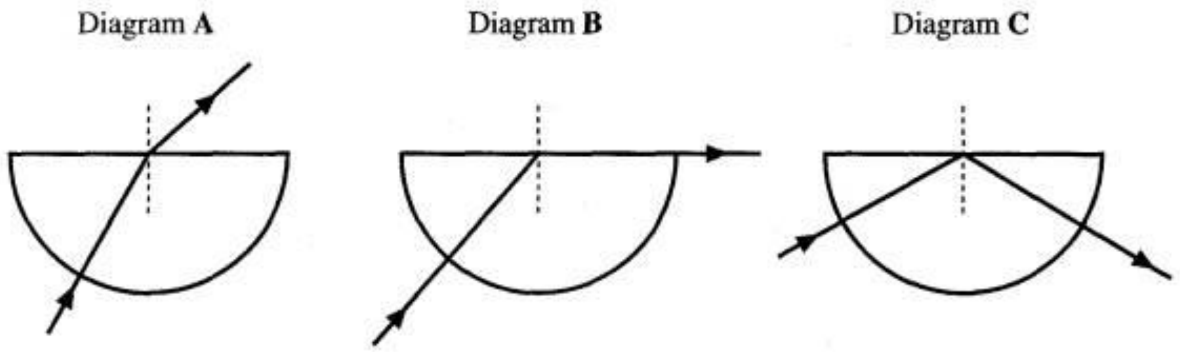
Measuring the critical angle

When light travels from a more dense to a less dense material (medium) e.g.from Perspex to air, it bends away from the normal. If the angle inside the Perspex is increased a point is reached where the angle in air equals 90 degrees. The angle in the Perspex which causes this is called the **critical angle.**



When the angle of incidence is smaller than the critical angle most of the incident light is refracted into the air.

When the incident angle is equal to the critical angle light is refracted into the air at 90 degrees.

When the incident angle is greater than the critical angle no light is refracted into the air. All light is reflected back into the prism.

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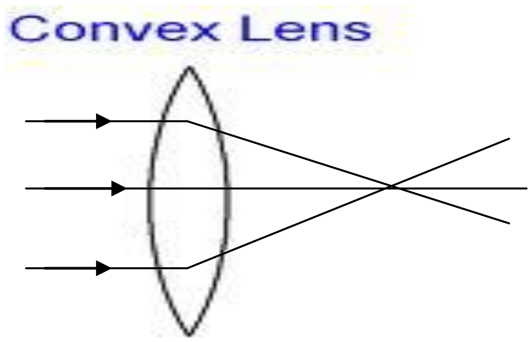
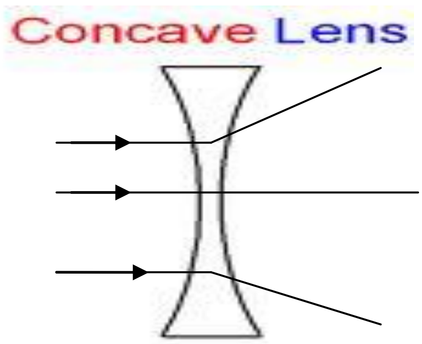
Lenses

Lenses make use of the effect of refraction that causes light to change direction.





When light rays pass through a convex lens they **come together (converge)**. When light rays pass through a concave lens they **move apart (diverge)**. The more curved a lens is the **greater** the effect on the light rays.

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Focal Length

Previously you found out that different shapes of lens affect light in different ways. A way of identifying the effect of a lens is to measure its focal length. The focal length is the distance from the centre of the lens to a clear image of a **distant** object.

Lenses however are normally identified by their power.

The focal length of a lens should be given in metres. The power of a lens is measured in a unit called the dioptre. It has the abbreviation, D. If a lens power is positive [+3D] it is a convex lens (converging). If a lens power is negative [-8D] it is a concave lens (diverging).

Calculating focal length.

$$f = \frac{1}{P}$$

Where f is the focal length of the lens in metres and
P is the power of the lens in dioptres.

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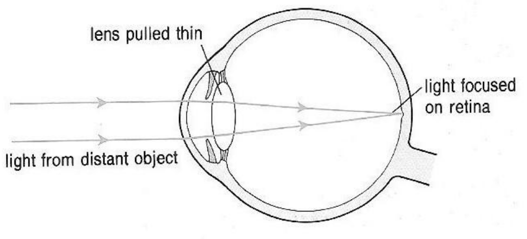
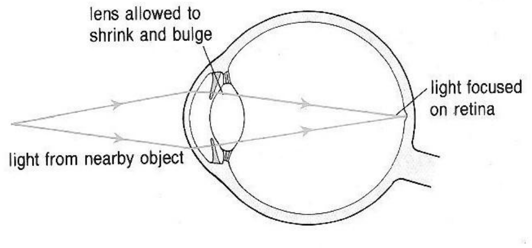
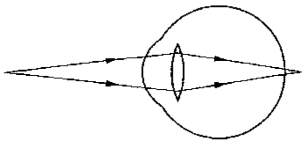
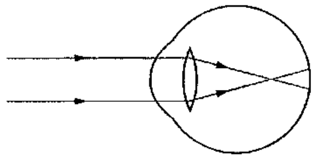
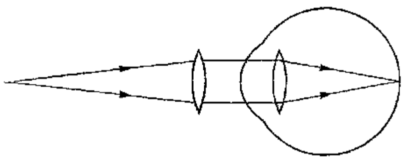
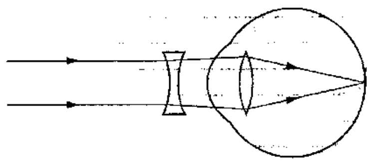
Long and short sight

There are two eye defects that we will discuss in this topic – **long-sightedness** and **short-sightedness**. People who are longsighted can only focus on objects which are far away but nearby objects appear blurry. People who are short-sighted can only focus on objects which are nearby but objects which are far away appear blurry. It is important to note that light from far away objects is considered parallel and light from nearby objects is considered diverging.
Therefore people who are longsighted can accommodate parallel rays and people who are short-sighted can accommodate diverging rays. The focus always lands on the retina.





Long-sighted	Short-sighted
People who are long-sighted can focus on objects far away	**People who are short-sighted can focus on objects close up**
When people who are long-sighted try to look at an object close up the lens of their eye cannot adjust enough to focus the rays onto the retina of the eye. The rays focus behind the retina, like this:	When people who are short-sighted try to look at an object far away the lens of their eye cannot adjust enough to focus the rays onto the retina of the eye. The rays focus in front of the retina, like this:
	
This means that they see an unfocused (blurry) image.	*This means that they see an unfocused (blurry) image.*
To correct this problem we need a lens, which will converge the rays before they enter the eye – a convex lens will do this, like this:	To correct this problem we need a lens, which will diverge the rays before they enter the eye – a concave lens will do this, like this:
	
A convex lens can be used to correct long-sightedness.	**A concave lens can be used to correct short-sightedness.**

3.4 Nuclear radiation

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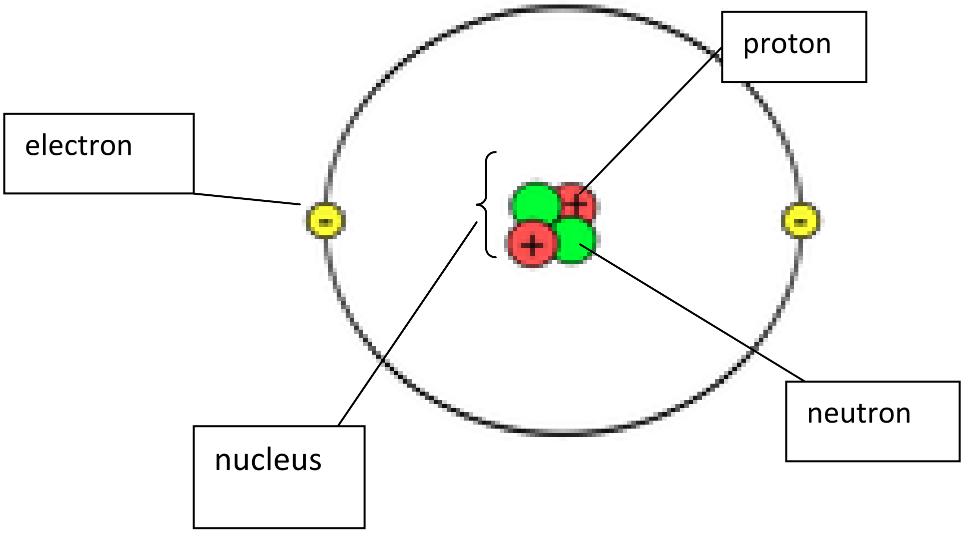
The atom



The above diagram shows a simple model of the atom (it is not to scale).

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Nuclear radiation

Nuclear radiation is so called because it originates in the nucleus of an atom. Nuclear radiation can come from natural sources such as cosmic rays and naturally occurring radioactive materials such as uranium. It can also come from artificial sources such as man-made radioisotopes such as plutonium.

Nuclear radiation can be used in medicine to sterilise instruments by killing germs and bacteria. It can also be used to kill the cells which make up a cancerous tumour, however care must be taken in this procedure as nuclear radiation can also kill or damage healthy cells . Nuclear radiation can also be used to examine the body through using radioactive materials in something called a **tracer**. This is a substance that is injected into the body and detected to analyse its progress through the body.

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We will look at three different types of nuclear radiation:

alpha α

beta β

gamma γ

type of radiation	nature	Minimum absorber
alpha	two protons and two neutrons (helium nucleus)	sheet of paper, few centimetres of air
beta	fast-moving electron	few cm of aluminium
gamma	electromagnetic wave	Several cm of lead

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Ionisation

The process by which nuclear radiation damages cells is known as ionisation. This is where electrons are removed from or added to an atom to leave a charged particle called an ion. If the atom gains an electron it has an overall negative charge and if it loses an electron it has an overall positive charge. Alpha radiation causes more ionisation than beta or gamma radiation.

Background radiation

Nuclear radiation is always present in our environment. This is known as **background radiation**. This can come from natural sources e.g. radon gas, cosmic rays or from man-made sources e.g. nuclear fallout from weapons testing and accidents at nuclear power stations.

Absorbed dose and equivalent dose

The amount of energy received by a substance per unit mass is known as the **absorbed dose**. This can be calculated by using the equation

$$D = \frac{E}{m}$$

where D is the absorbed dose in grays (Gy)

E is the energy in joules (J)

and m is the mass in kilograms (kg)

This does not tell the whole story of how a person would be affected by nuclear radiation. It does not take into account the type of radiation encountered.

The **equivalent dose** allows us to take the type of radiation into account. It is calculated by using the equation $H = Dw_R$

where H is the equivalent dose in sieverts (Sv)

D is the absorbed dose in grays (Gy)

and w_R is the radiation weighting factor.

Alpha radiation has a radiation weighting factor of 20, whereas beta and gamma radiation both have a radiation weighting factor of 1.

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Activity

The **activity** or a radioactive source is a measure of how many radioactive particles are released every second. It is calculated by $A = \frac{N}{t}$

where A is the activity in becquerels (Bq)

N is the number of nuclei that decay

and t is the time in seconds (s)

The activity of a source decreases over time. Whilst the decay of an individual atom is completely random and unpredictable, the time taken for half the atoms in a sample of a particular material to decay can be predicted as it will always be the same. This is known as the **half-life**. The half-life is the time taken for the activity of a radioactive source to fall to half of its original value.

Different materials have different half lives:

hydrogen-7	1×10^{-22} s	californium-254	60.5 days
carbon-15	2.5 s	plutonium-238	87.7 years
nobelium-259	58 minutes	uranium-238	4.5 billion years

Half-life calculations

Example 1

If a source of activity 8 000 Bq has a half-life of 6 days, what activity will it have after 18 days?

1 half-life = 6 days

18 days = 18 ÷ 6 = 3 half-lives.

$8\,000 \xrightarrow[1]{} 4\,000 \xrightarrow[2]{} 2\,000 \xrightarrow[3]{} 1\,000$

The activity is 1 000 Bq.

Example 2

Calculate the half-life of a source that decreases in activity from 32 kBq to 8 kBq in 24 days.

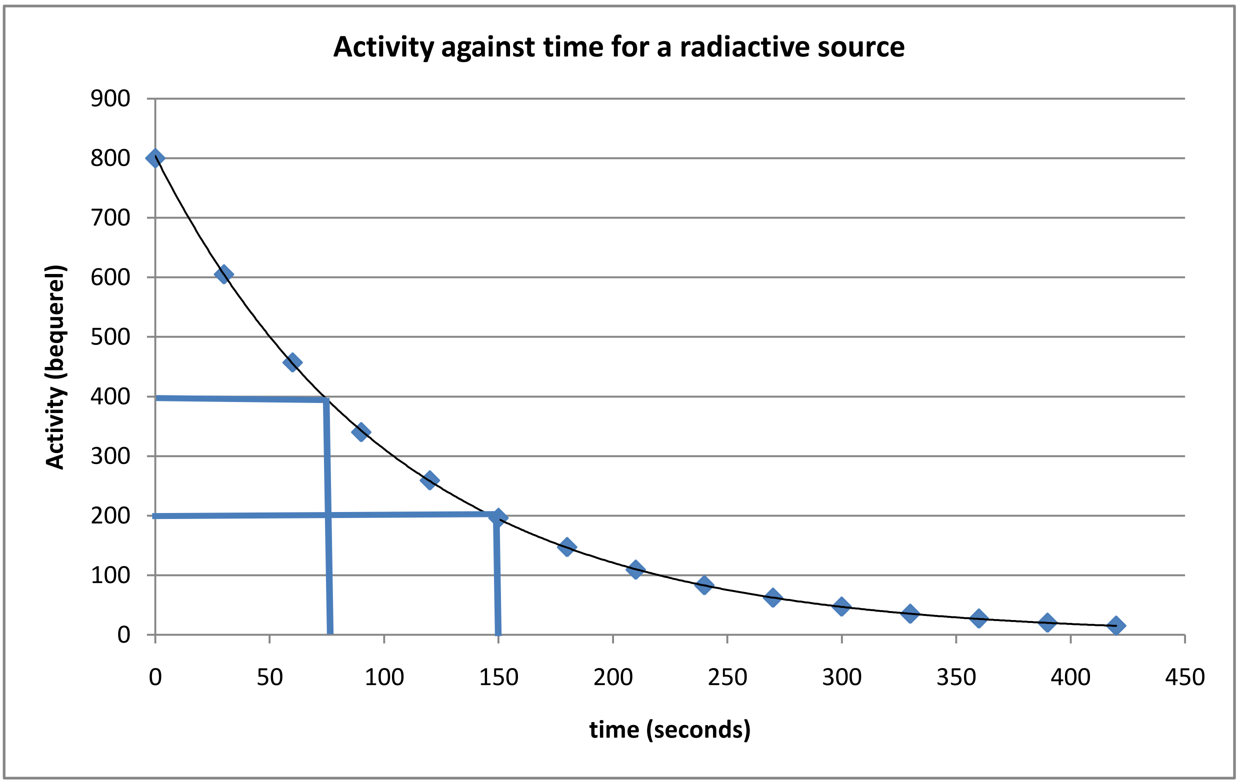
$32 \xrightarrow[1]{} 16 \xrightarrow[2]{} 8$

2 half-lives = 24 days

1 half-life = 12 days

Half-life calculations continued

Half-life can be calculated by graphical methods. A graph of activity against time can be plotted and half-life worked out from it.



- Choose any value of activity on the y-axis (say 400 Bq) and draw a line in to meet the curve.
- From this point on the curve draw a line to meet the time on the x-axis.
- Do this again for a value of activity that is half of the first (200 Bq in this case).
- The **difference** between the values on the time axis is the half-life of the source.

For the above example this is 150 – 80 = 70 seconds.

Selecting a radioactive source with the correct half-life is important when choosing it for an application, for example:

- It would not be wise to choose a radioactive tracer with a long half-life as this would remain active within the body for too long a time.
- It may be be necessary to choose a source with a long half-life to examine an oil pipeline for cracks.

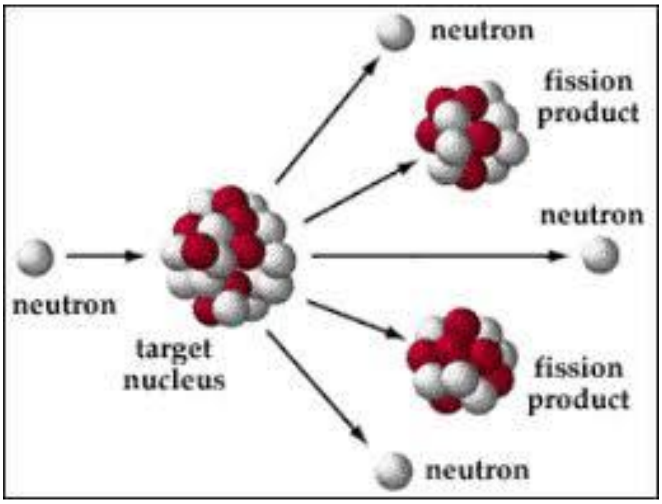
Do some research of your own to find out about the importance of half-life in the application of radioactive substances.

N5

Energy and nuclear radiation

There are two ways in which nuclear radiation can be used to generate energy.

1. Fission



If a neutron is fired at a uranium 235 nucleus, it becomes unstable and separates into two smaller nuclei and releases some more neutrons. The mass of these nuclei and neutrons is slightly less than the mass of the original nucleus and neutron. Using the equation $E = mc^2$, where *m* is the mass lost and *c* is the speed of light, we can calculate the energy released in each fission reaction. If the neutrons that are released are captured by other uranium 235 nuclei, the process can be repeated. This is known as a **chain reaction**.

In nuclear power stations, the energy released is used to heat water to produce steam to turn a turbine. This drives a generator which produces electricity.

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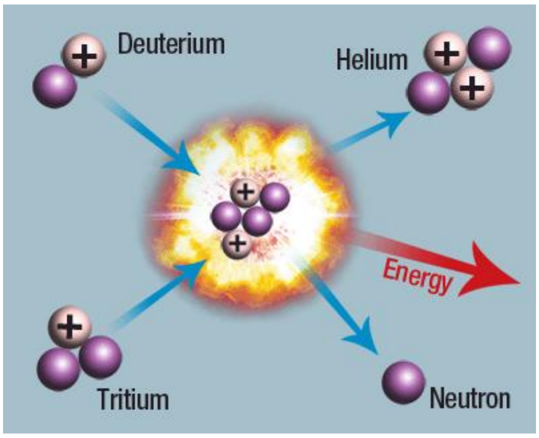
Energy and nuclear radiation (continued)

2. Fusion



Fusion is a process where two smaller nuclei are combined to create a larger nucleus. Again, the total mass of the products of this reaction is less than the total mass before the reaction, allowing us to calculate the energy released by using the equation $E = mc^2$. It is thought that fusion would allow us to generate far more energy than fission at much lower risk, however we are currently unable to do this economically. Fusion is the process in which stars convert fuel to light and heat.

Note: It is important that you do not misspell fusion or fission!

Using nuclear radiation to produce electricity reduces the amount of carbon dioxide released into the atmosphere. Carbon dioxide is a greenhouse gas which helps contribute to global warming. However, nuclear reactors produce radioactive waste which needs to be stored for thousands of years before it is safe.